THE TOP QUARK AND THE HIGGS BOSON MASS FROM LEP SLC AND CDF DATA

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Abstract

The impact of the new experimental data from LEP, SLC and CDF on the top quark mass m_{top} and the Higgs boson mass m_{Higgs} is investigated. The determinations of m_{top} and of an upper bound on m_{Higgs} are given, taking into account the experimental error on the QED coupling constant α_{em} and on the b quark mass m_b. The relevance of higher order theoretical uncertainties is pointed out.

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Up to now the four LEP experiments at CERN collected roughly 8×10^6 Z^0 bosons, of which 3×10^6 have been produced in the 1993 resonance scanning. This led to a substantial improvement in the measurement of the Z^0 parameters such as M_Z, Γ_Z, Γ_b, the asymmetries and so on [1]. Meanwhile other relevant experimental results have been achieved. First, the experiment SLD at SLAC measured the value of the left-right asymmetry on a sample of 5×10^4 Z^0's, but with longitudinally polarized electrons ($P \simeq 0.62$), reaching an accuracy competitive with LEP determination [2]. Second, the experiment CDF at FERMILAB improved the measurement of M_W, leading to a better determination of the ratio M_W/M_Z [3]. Last, but not least, very recently CDF collaboration claimed for evidence of top quark production in

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$\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV, quoting a value for the top quark mass of $m_{top} = 174 \pm 10^{+13}_{-12}$ GeV [4].

At this point, it can be relevant to study the impact of the new experimental data on the determination of the fundamental parameters of the Minimal Standard Model, which is the goal of the present short note. Moreover, in the light of the presently achieved experimental accuracy, two more items should be taken into account. Firstly a particular care has to be devoted to the effect of the experimental error on the electromagnetic coupling constant α_{em}, coming from the parameterization of the light quark contribution to the vacuum polarization [5], and on the b quark mass m_b. Secondly the theoretical uncertainty due to higher order effects in the Standard Model predictions has to be taken into account and properly quantified. It goes almost without saying that everything we are going to show is largely based on data presented at the winter conferences; in particular the averaging of R_b among the four LEP experiments is complicated and very preliminary so that this and other numbers, such as the correlation matrix, could very well change [6].

In order to attain the above stated goal, the electroweak library of the code `TOPAZ0` [7] has been used. Very recent developments in the field of electroweak and QCD radiative corrections, such as $\mathcal{O}(\mathcal{G}_{\mathcal{F}}^{\in}\Updownarrow_{\sqcup\wr}^{\triangle}\surd)$ in $\Delta\rho$, QCD corrections including b quark mass effects with running b quark mass and full $\mathcal{O}(\alpha_{\rceil\Updownarrow}\alpha_f)$ effects [8], have been taken into account [9].

The indirect determination of the top quark mass m_{top} and the Higgs boson mass m_{Higgs} have been studied in some detail. The data used are the experimental measurements of the Z^0 parameters, namely M_Z, Γ_Z, R, R_b, σ_{had}, g_V/g_A or the deconvoluted asymmetries, plus the best determination of the ratio M_W/M_Z (UA2 + CDF, weighted average). When the ratio g_V/g_A has been used in place of the asymmetries, the inclusion of the SLD measurement has been performed by taking the weighted average of the LEP and SLD experimental data (see Table 1). The experimental error on $\alpha_{em}(M_Z)$, $1/\alpha_{em}(light) = 128.87 \pm 0.12$, and on the b quark mass m_b, $m_b = 4.7 \pm 0.2\,$GeV, and the experimental value of the top quark mass m_{top} as given by the direct determination of CDF ($m_{top} = 174 \pm 17$ GeV) have been included by proper penalty functions. Moreover we have used the presently available elements of the correlation matrix [10].

Let us begin with the top quark mass determination. The situation is

well summarized in Figs. 1-4, where χ^2 versus m_{top} is shown. For a given m_{top} the corresponding χ^2 has been obtained by minimizing the χ^2 function with respect to M_Z and α_s for m_{Higgs} kept fixed at $m_{Higgs} = 300$ GeV (M_Z constrained at 91.190 ± 0.004 GeV, no constraint on α_s). Fig. 1 shows the χ^2 in the following situations (M_W/M_Z is always included): LEP data only (dash-dotted line), LEP + SLC data (solid line), LEP data + CDF constraint (dotted line) and LEP + SLC data + CDF constraint (dashed line). The ratio g_V/g_A is used as summarizing the asymmetry data. The uncertainty due to the error on $\alpha_{em}(M_Z)$ and m_b is propagated in the theoretical part of the χ^2.

Fig. 2 shows the same content as Fig. 1, but with $\alpha_{em}(M_Z)$ and m_b kept fixed at their central value, 1/128.87 and 4.7 GeV respectively. In Fig. 3 the effect of propagating the error on $\alpha_{em}(M_Z)$ and m_b is pointed out by comparing a fit in which the error is taken into account (dashed line) with a fit in which it is neglected (solid line). Fig. 4, at last, is the same as Fig. 1 but with the individual asymmetries used in place of the combined value of g_V/g_A. The best determination of m_{top} can be considered the one in which the whole set of experimental information is used, namely the one in which LEP + SLC data + CDF constraint (+ M_W/M_Z) are used, together with the propagation of the errors on $\alpha_{em}(M_Z)$ and m_b. In this case the best fit gives

$$m_{top} = 174.0^{+9.3+12.0+0.2}_{-9.6-12.5-3.4} \quad \text{GeV}, \tag{1}$$

where, according to a commonly accepted procedure, the central value refers to $m_{Higgs} = 300\,$GeV, the first error is statistical, the second one is obtained by allowing m_{Higgs} to vary from 60 to 1000 GeV and the third one is due to higher order theoretical uncertainties. At best fit one obtains $\alpha_s = 0.124$ and $M_Z = 91.190$ GeV. The last uncertainty is connected to the unknown electroweak higher order terms, the truncation or not in perturbation theory, the electroweak and QCD scales and the factorization or not of QCD radiation. Actually the central value for m_{top} deserves some additional explanation. It has been derived by choosing some of the options on the treatment of higher order EW terms such that we get the best agreement between `TOPAZ0` and the other existing codes (`BHM` [11], `LEPTOP` [12] and `ZFITTER` [13]). If we use the same data set (LEP + SLC data + CDF constraint) and perform a three parameter fit (M_Z, m_{top}, α_s) at m_{Higgs} fixed, then the minimum of the χ^2

corresponds to $m_{Higgs} = 64$ GeV (more about this later, see table 2). There is of course some degree of arbitrariness in fixing m_{Higgs} to 300 GeV and one could ask what happens if we derive results for m_{top} at the best value for m_{Higgs} kept fixed. Therefore we have performed a two parameter fit with respect to M_Z and α_s for the Higgs mass fixed at 64 GeV. We obtain

$$m_{top} = 161.9^{+9.4}_{-9.7} \quad \text{GeV}, \tag{2}$$

corresponding to $\alpha_s = 0.122$. This result is confirmed by a three parameter fit on the same data set, namely a fit to M_Z, α_s and m_{Higgs} (without any constraint on m_{Higgs}), giving

$$m_{top} = 161.9^{+13.9}_{-11.4} \quad \text{GeV}, \tag{3}$$

corresponding to $\alpha_s = 0.123$ and $m_{Higgs} = 64$ GeV. Finally, by performing the same type of fit with the penalty function on $m_{_H}$, only slightly different results are obtained, namely

$$m_{top} = 162.4^{+13.4}_{-9.6} \quad \text{GeV}, \tag{4}$$

with $\alpha_s = 0.122$, $m_{Higgs} = 68.5$ GeV. All these values are found to be in good agreement with the results very recently obtained in [15].

Before making any comment it is worth noting that a slightly different situation appears if we neglect the SLD data. Actually a canonical fit at $m_{Higgs} = 300$ GeV gives

$$m_{top} = 168.1^{+9.6+11.5}_{-9.9-11.8} \quad \text{GeV}, \tag{5}$$

where the first error is statistical and the second one is due to a variation of m_{Higgs} from 60 to 1000 GeV, whereas a fit in which m_{Higgs} is left free provides

$$m_{top} = 164.0^{+14.7}_{-13.7} \quad \text{GeV}, \tag{6}$$

with at best fit $m_{Higgs} = 187$ GeV and $\alpha_s = 0.124$. The difference on the central values for m_{top} is smaller than the corresponding one appearing when the SLD data is included, reflecting the fact that the SLD asymmetry is about 3σ away from the corresponding LEP measurement. As a consequence of this the value of m_{Higgs} is driven towards the direct search boundaries and the central value for m_{top} depends strongly on the type of fit performed. On the

contrary we do not find large ($\approx 10\,\mathrm{GeV}$) deviations on m_{top} from different fits if the SLD data is excluded. At last excluding CDF constraint, i.e for the data set LEP + SLC ($+M_W/M_Z$), the best fit gives $m_{top} = 174.0^{+11.0+17.0+0.3}_{-11.7-18.5-4.9}$ GeV, in good agreement with the result quoted in [16]. Moreover for the LEP data alone ($+M_W/M_Z$) we obtain $m_{top} = 165^{+12+17}_{-13-19}$ GeV in agreement with [17].

For the sake of comparison, it is worth quoting the value of α_s as obtained from a fit to R, which gives

$$\alpha_s = 0.1258 \pm 0.0060^{+0.0029+0.0007}_{-0.0031-0.0014}, \tag{7}$$

where the first error is the experimental one, the second one comes from $m_{top} = 174 \pm 17$ GeV and $m_{Higgs} = 60 - 1000$ GeV and the last one is again due to theoretical uncertainty. This value has been obtained along the same lines of the one presented in [18]. If on the other hand we perform a fit to M_Z, m_{top}, m_{Higgs} to the LEP + SLC data + CDF constraint for α_s fixed and derive the $\chi^2(\alpha_s)$ distribution, then we get $\alpha_s = 0.1218 \pm 0.0047$. The same fit excluding SLC gives instead $\alpha_s = 0.1242^{+0.0053}_{-0.0050}$.

At this point some comments are in order. The SLC measurement of A_{LR} increases the fitted m_{top} value of about 6-9 GeV with respect to the value given by LEP data only. Moreover when the asymmetries are individually entered in the fit instead of fitting the combined value of g_V/g_A, the inclusion of the SLC measurement leads to a clear rise of the χ^2. This confirms that the SLC value is about 3 σ away from the combined LEP value of g_V/g_A. Including the CDF constraint increases the fitted value of m_{top} of about 3 GeV if SLC is not included, whereas it gives no effect on the central value of m_{top} if SLC is included in the fit. In any case CDF constraint reduces the statistical error on m_{top} of about 2 GeV and the error on m_{top} due to the uncertainty on m_{Higgs} of about 5 GeV. The uncertainty on the central value of m_{top} generated by the error on $\alpha_{em}(M_Z)$ and m_b can be quantified in about 2 GeV and finally the one due to the theoretical ambiguity on higher orders can be estimated to be around 4-5 GeV. It is also worth noting that the only Z^0 parameter which at present is *non-standard* is R_b, whose experimental value is larger than expected of about two standard deviations, if indeed the top quark is around 174 GeV. Excluding R_b from the fit leads to an increasing of m_{top} of 4-6 GeV.

As far as m_{Higgs} determination is concerned, the χ^2 as a function of m_{Higgs} has been obtained by means of a three parameter fit with respect to M_Z, m_{top}

and α_s at m_{Higgs} fixed. In principle one could expect some influence of the direct observation of the top quark on the theoretical predictions for m_{Higgs}. In order to point out such an effect the direct determination of m_{top} by CDF at $m_{top} = 174 \pm 17$ GeV has been taken into account by including a proper penalty function. The situation is well described by the results shown in Table 2 (7 observables means fitting g_V/g_A, 11 observables means fitting the asymmetries). For the most complete set of data (LEP + SLC + CDF), the curves at 95% C.L. in the m_{top}–m_{Higgs} plane are also shown in Fig. 5 for three different values of α_s and including the Higgs mass penalty function.

Predictions and corresponding errors from a fit to LEP+SLD+CDF data (average g_V/g_A) are given in Table 3, where $\sin^2\vartheta(b)$ includes the universal $Z \to b\bar{b}$ vertex corrections. The effect of the SLD measurement is to bring the m_{Higgs} upper limit well below 1 TeV almost independently of the CDF constraint. The reason is that SLD wants m_{top} large and m_{Higgs} and α_s small in order to readjust as much as possible the LR asymmetry. The constraint on m_{Higgs} is more a symptom of the clash between SLD and LEP than a reliable hint of m_{Higgs} small. The information carried by the CDF constraint requires a careful examination. Actually it has been verified that without the CDF constraint the χ^2 shape as a function of m_{Higgs} is unstable with respect to *normal* fluctuations of the experimental data in the large m_{Higgs} tail, in agreement with [14], whereas the inclusion of the CDF constraint renders the tail more stable under small perturbations of the data. In the case of m_{Higgs} determination the theoretical uncertainty on EW higher orders plays a very relevant role. The situation is described in Fig. 6, where the χ^2 as a function of m_{Higgs} is plotted for the most complete set of data LEP + SLD + CDF (7 observables). Actually the χ^2 is not a single curve but instead the whole band inside the two solid lines, describing the theoretical uncertainty on the Standard Model pseudo-observables. Inside this band we have reported the χ^2 distribution as derived from `TOPAZ0` in its default settings and also the one obtained from `TOPAZ0` adapted for comparisons with other existing codes. This theoretical uncertainty leads to a corresponding uncertainty on the upper limit of some 200 GeV.

In conclusion, the last LEP, SLD and CDF data bring to an indirect determination of m_{top} at $m_{top} = 174^{+9.3+12.0+0.2}_{-9.6-12.5-3.4}$ GeV and allow to discuss an upper limit on m_{Higgs} with some improvement with respect to the past.

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Observable	
M_Z	91.1899 ± 0.0044 GeV
Γ_Z	2497.1 ± 3.8 MeV
R	20.789 ± 0.04
R_b	0.2210 ± 0.0019
σ_{had}	51.51 ± 0.12 nb
A^l_{FB}	0.0170 ± 0.0016
A^τ_{pol}	0.150 ± 0.010
A^e	0.120 ± 0.012
A^b_{FB}	0.0970 ± 0.0045
A^c_{FB}	0.072 ± 0.011
A_{LR}	0.1668 ± 0.0079
g_V/g_A(LEP)	0.0711 ± 0.0020
g_V/g_A(LEP+SLD)	0.0737 ± 0.0018
M_W/M_Z	0.8814 ± 0.0021

Table 1: *Experimental values*

Set of data	χ^2_{min}	m_{Higgs} (GeV)	
		best value	95% C.L.
LEP + SLD + CDF	7.5/7	64	580
LEP + CDF	7.8/7	187	1354
LEP	6.9/7	76	986
LEP + SLD	6.6/7	39	400
LEP + SLD + CDF	17.1/11	53	511
LEP + CDF	9.7/11	165	1237

Table 2: *Predictions for* m_{Higgs}

Observable		stat.	Higgs	theor.
M_W	80.321 GeV	± 0.052	± 0.019	${}^{+0.004}_{-0.001}$
$\sin^2\theta(l)$	0.2319	± 0.0003	${}^{+0.0002}_{-0.0004}$	${}^{+\simeq 0}_{-0.0002}$
$\sin^2\theta(b)$	0.2331	± 0.0002	± 0.0005	${}^{+\simeq 0}_{-0.0002}$

Table 3: *Our predictions for M_W and $\sin^2\theta(l,b)$ for a fit to LEP+SLD+CDF data.*

This figure "fig1-3.png" is available in "png" format from:

http://arXiv.org/ps/hep-ph/9407246v1